Published in final edited form as:

Gait Posture. 2018 September ; 65: 157–162. doi:10.1016/j.gaitpost.2018.07.175.

Biomechanical Evaluation of Virtual Reality-based Turning on a Self-Paced Linear Treadmill

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Abstract

Background: Patients with brain injuries such as Parkinson's disease or stroke exhibit abnormal gait characteristics especially during gait transitions such as step initiation and turning. Since such transitions could precipitate falls and resultant injuries, evaluation and rehabilitation of non-steady state gait in those patients are important. Whereas body weight supported treadmill training (BWSTT) provides a safe and controlled environment for gait training, it is unable to adequately train for gait transitions since the typical linear treadmill does not allow for changes in walking direction and natural fluctuations in speed.

Research question: This paper verifies if the suggested virtual reality (VR) based walking interface combined with the unidirectional treadmill can stimulate the user to initiate turning gait.

Methods: To validate whether initiation of turning was successfully achieved with the proposed walking system, we developed the VR-based walking interface combined with the self-paced treadmill and compared kinematics, kinetics, and muscle activation levels during the VR-based

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Conflict of interest statement

Declarations of interest: none

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turning and over ground (OG) turning as well as between straight walking and turning within conditions.

Results: Despite walking on a linear treadmill, subjects showed significant increases in head rotation, pelvic rotation, right hip abduction, left hip adduction, foot progression, medial-lateral ground reaction forces, right medial hamstring activation level, and changes in step width during the VR turn compared to straight walking.

Significance: The developed VR-based turning interface can provide a safe and controlled environment for assessment of turning in healthy controls and may have a potential for assessment and training in patients with neurological disorders.

Keywords

turning; virtual reality system; self-paced treadmill; gait rehabilitation

INTRODUCTION

Recent studies on gait disorders in patients with Parkinson's disease (PD) and stroke have found that patients have difficulties during gait transitions such as step initiation, termination, and turning. They often exhibit increased tremor, hesitation, a loss of stability, or even falls. This phenomenon is termed freezing of gait (FOG) [1–3] known to be caused by problems in the basal ganglia circuit [1, 4–6].

Since daily gait consists of both steady state walking and transitions such as accelerations, decelerations, and directional changes [7, 8], it is important to include these in gait assessment and rehabilitation. Patients with brain injuries have fall rates of 40–70 % [9] during such gait transitions. Moreover, falls often cause other secondary complications or injuries.

BWSTT with a commercial linear treadmill has been widely used for gait rehabilitation, but it is currently limited in its ecological validity because it essentially provides stepping practice in a single direction. Since directional changes have also been shown to elicit FOG in PD [10, 11] we undertook the challenge of trying to simulate this in our VR-based linear treadmill setup.

Previous studies reported the effect of VR on human gait by observing kinematic and kinetic changes in VR versus real environments. Specifically for turning, some researchers found that directional changes in the VR corridor could evoke head rotation and actual turning in overground [12, 13] or on omnidirectional treadmills [14, 15]; however it has not yet been shown whether VR with the linear treadmill could evoke turning mechanisms similar to OG turning.

This study aimed to verify whether it is possible to initiate turning on a VR-based self-paced linear treadmill. We analyzed biomechanical data from the following conditions: 1) VR-evoked turning on a self-paced linear treadmill, 2) straight walking on the same treadmill, 3) OG turning, and 4) OG straight walking. We compared the two turning conditions and we compared each turning condition to their respective straight walking condition. Analysis of

turning biomechanics on the VR treadmill system could determine whether the proposed VR system can evoke similar turning mechanisms as in OG walking.

MATERIALS AND METHODS

Ten healthy young adults (age: mean 25.0 years, range 22.1–35.1 years; 5 males, 5 females) participated in the study. All subjects signed informed consent forms prior to participation, and the study was approved by the institution's Internal Review Board at the National Institutes of Health. We did not specifically instruct them how to turn on the treadmill in response to the VR cues, so we could evaluate whether the VR interface would intuitively stimulate the intention of natural turning mechanics.

To develop the VR-based turning interface, we combined the VR projection system and the self-paced walking treadmill (Fig. 1). Turning and self-paced walking were implemented by displaying a 90-degree direction change in the VR corridor and enabling the belt speed to be controlled by the intention to change direction and speed detected from movements of user's body parts. To assess the realism of a VR-based treadmill interface, biomechanical parameters were analyzed for VR turning versus VR straight walking, VR turning and OG turning, and OG turning versus OG straight walking. The head rotation angle as an intention of turning, changes in joint movements, ground reaction forces, muscle activity, and step length and width were measured. VR and OG turning experiments were conducted using the VR corridor on a linear treadmill and an L-shaped corner on a prescribed OG path, respectively. Due to space limitations in the laboratory, OG turns in only one direction (left turns) were performed and only the left VR turns were used in the comparisons.

Turning in the VR was controlled by head rotation and the VR was synchronized to move at the same speed as the treadmill. The VR created with 3D rendering software (Unity Technologies, US) consisted of a 42-meter hallway with three 90-degree turns (right, left, and left, consecutively). An integral of the head rotation angle was used to indicate turning intention when calculating the rotation angle of the VR corridor (Fig. 2). To prevent the VR (Φ_{VR}) from rotating back to the orientation prior to the turn as the head rotates back in line with the pelvis, the head rotation angle (θ_{head}) was integrated as follows:

$$\Phi_{VR} = K_{head} \int \theta_{head} dt, \quad (1)$$

where K_{head} represents a constant gain value of 3.65 that adjusts the amount of VR rotation angle per head rotation angle.

To improve the realism of VR and help users perform self-paced gait on the treadmill, the speed of treadmill belt was adjusted to accomplish the user's intended speed. For self-paced walking, the motion capture system (Vicon Motion Systems, US) tracked the real-time velocities of the pelvis and feet and a custom control algorithm [16–18] estimated a target speed of the belt (Fig. 2). The speed of the treadmill was then controlled to track the estimated target speed in real-time. Conceptually, the self-paced treadmill control reacts quickly to speed up or slow down based on the movement of the pelvis and feet.

OG straight walking and left OG turning were achieved by walking along the L-shaped path starting at the top of the L (Fig. 1). A portable screen was placed vertically on the inside corner of the L-shaped path to serve as the wall. The left turn had a 6 m long straight section followed by 4 m section after the turn.

Each subject performed 10 VR corridor trials with 20 left turns (2 per trial), 5 trials on the L-shaped OG path and OG straight path. Kinematic, kinetic, and EMG data were collected simultaneously. Motion capture data was also collected, and reflective markers were placed bilaterally on the ASIS, PSIS, thigh, shank, medial and lateral knees, medial and lateral ankles, heel, between 2nd-3rd metatarsal, and 5th metatarsal. Additionally, four markers were placed on the head. The kinematic model and variables were created in Visual3D (C-Motion, US). Kinematic variables of interest were head rotation relative to the lab, head rotation relative to the pelvis, hip abduction/adduction, and foot progression angles. Surface electromyography (EMG) was collected at 1080 Hz by using wireless sEMG sensors (Delsys Inc., US) for four bilateral muscles: tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), and semitendinosus (Medial Hamstrings, MH). EMG data were filtered with a 5th order Butterworth bandpass filter with low and high pass cut-off frequencies of 10 and 400 Hz, respectively. To compare muscular effort between conditions, a linear envelope using a mean absolute value (MAV) and a root mean square (RMS) value of the EMG signal were calculated. Medial-lateral ground reaction forces exerted by each leg were also collected during VR walking only using the instrumented treadmill (Bertec, US). Kinematic and kinetic data were collected at 120 and 1080 Hz and were then filtered with a 5th order Butterworth low-pass filter with cut-off frequencies of 10 and 20 Hz, respectively.

To categorize collected data into turning and straight walking conditions and compare those conditions, additional post-processing was done by custom programs in Matlab (Mathworks, US). Head rotation angle in the transverse plane was used to identify the beginning of the turn for both VR and OG. The foot strike immediately preceding the head angle exceeding a threshold of 20% of the peak head rotation angle during the turn was identified as the start of the turn. To compare sequential movements of the head, pelvis, and foot between the VR and OG turn, relative onset of rotation in head, pelvis, and foot referenced to the start of turn were identified when the joint angle was outside of the mean straight walking angle plus two standard deviations [13]. To check similarities in temporal-spatial parameters, step lengths and step widths were calculated from the left and right foot positions at foot strike during the identified turning stride [19]. Since this paper focuses on turning initiation, the first gait cycle of the turn and the gait cycle preceding and following were analyzed for the step lengths and widths. These cycles were individually compared to the average of the three gait cycles immediately preceding.

Statistical analysis was performed using SPSS 19 (IBM, US). Repeated measures ANOVA with four factors (VR left turn, OG left turn, VR straight, OG straight) was performed to assess for differences with post hoc analyses performed as indicated. A paired samples t-test compared step length and width between VR turn and VR straight.

To assess the realism of the VR turning seemed to the subjects, each was asked to score the VR-based turning on a scale of 1 (felt totally different compared to OG turning) to 10 (same as OG turning) after each test.

RESULTS

Nine out of ten subjects were able to initiate turning in the VR corridor successfully, and the one who was unable was excluded from the analysis. Peak head rotation angle relative to the lab and the pelvis, pelvic rotation, left hip abduction and adduction, right hip abduction, and left and right foot progression angles were all significantly different during VR turning compared to VR straight walking. Kinematic mean values for each condition are listed in Table 1.

When comparing the OG and VR turning conditions, peak head rotation relative to the lab, pelvic rotation, left hip adduction, and left and right foot progression were all significantly smaller during VR turning than OG turning ($p < 0.001$). Peak right hip abduction, adduction and head rotation relative to the pelvis were not significantly different between the two turning conditions (Table 1).

During OG turning, the head was the first segment to rotate on 77.3% of trials and rotated before the pelvis on 97.7% of trials. During the VR turn, the head was the first segment to rotate on 93.2% of trials. The head rotated before the pelvis on 82.1% of VR trials, but only 1.9% of trials had the pelvis rotate before the head. The pelvis never exceeded the mean plus two standard deviations on the remaining 16% of trials. There was not a clear pattern of the order of foot rotation for either OG or TM.

The initial gait cycle of the VR turn did not have a significantly different step length ($p=0.627$) and step width ($p=0.771$) than the steps leading up to the turn during the straight walking (Fig. 3). The gait cycle before the start of the turn did have a significantly longer step length ($p=0.041$) and slightly shorter step width, although not significant ($p=0.084$). The gait cycle following the start of the turn trended to shorter step length ($p=0.073$) and had a significantly longer step width ($p=0.045$) (Fig. 3).

Subjects exerted an increased lateral force on the ground at the same time as peak left foot progression during the VR turning (Fig. 4). In contrast to OG turning, the stance leg on the side opposite to the turn also exerted increased lateral forces.

Though MG showed greater activation in both limbs during OG turning than OG straight walking, right and left MG did not show a significant difference between VR turning and VR straight walking. Right MH showed the larger magnitude of EMG during VR and OG turning than VR and OG straight walking, respectively. TA on both limbs showed larger activation levels during OG turning than OG straight walking (Fig. 5). In VR walking, the EMG activation in both right and left TA increased small amounts, but the difference was slight and not statistically significant ($p=0.48$ and 0.36 for right and left TA, respectively). Similar to the OG turning, the right MH showed significantly increased activation during the VR turning than the VR straight walking.

The average score for how realistic the developed VR system felt to the subjects was 7.11 ± 1.08 out of a possible 10 points.

DISCUSSION

Subjects were successful in initiating a turn in the developed VR system, as evidenced by the significant increase in lower limb joint angles, medial GRF and muscle activation levels during VR turning compared to VR straight walking. Although the amount of rotation angle was significantly smaller than OG turn due to the limitation of linear treadmill not allowing the feet to execute a full turn, this result still provides enough evidence that the proposed VR interface can initiate turning mechanisms on a linear treadmill. In addition to physically initiating the turn, participants reported turning in the VR system as seeming realistic (7.11/10 on the questionnaire).

Similar magnitude and timing in the head-pelvis rotation angle were found in both OG and VR turning which means that the proposed system can evoke user's intention to turn on the VR system. Although global head rotation angle relative to the lab in VR turning was smaller than OG turning, both VR and OG turning conditions showed similar ($p = 0.96$) maximum magnitudes of head rotation angle relative to the pelvis during turns. Such results are in line with the previous results showing that the visual cue of rotating the VR corridor could evoke actual turning [13] in the OG walking.

Previous researchers reported that a sequential rotation of the head, trunk, pelvis, and foot could be found during an OG turn, and a similar order of rotations was evoked by the suggested VR turning gait system. Subjects in our VR system actually turned their heads first more consistently than in the OG turning condition. Previous research of an OG turn found the head to initiate rotation first, followed by rotation of the trunk [20–22], pelvis [23], and then the lateral movement of feet [23]. Our study found the head to rotate prior to the pelvis in 97.7% of OG turns and 82.1% of VR turns, but only one subject was lower than 81%. Foot rotation, however, did not show a consistent pattern in onset of rotation compared to those of head and pelvis. During OG turning one or both feet rotated prior to the pelvis on 86.4% of trials, which is different than previously reported [23]. The VR turning had a lower percentage of one or both feet rotating before the pelvis at 58% of trials. A limitation of our OG turn is that subjects were constrained to turn within the motion capture space, so it is possible a more natural turn would involve a wider turn with a more consistent sequence of segment rotations.

When comparing the initial steps of the turn to the preceding steps, it appears that there was some attempt at preparation for the turn. The gait cycle prior to head rotation was significantly longer in step length and the shorter step width approached significance. The gait cycle where head rotation was initiated was not significantly different from straight walking. However, the following gait cycle had a significantly larger step width and shorter step length that approached significance; this gait cycle is similar to OG turning results [19]. Despite being confined to a limited area on the treadmill, subjects still significantly changed step lengths and widths during the initiation of a turn.

In line with the increase in step width, right hip abduction and left hip adduction also increased (Table 1). Since such changes in step width and length were known to be related to deceleration and kinetic changes such as GRF in the M-L direction during turning [19], our results imply that the subjects could also show similar kinetic changes in the M-L GRF required to change direction.

Subjects also exerted an increased lateral force on the ground during the VR turn which is consistent with the previous result that reported increased lateral force during OG turn in order to change momentum in the direction of the turn [20]. Such an increase in lateral force seemed to be accomplished by planting the foot outward, rotating the pelvis, and changing the direction only, and not the magnitude, of propulsive force. This could be attributed to the lack of increased muscular effort in plantar flexors during OG turning (Fig. 5). Interestingly, both legs exerted nearly the same amount of increased lateral force in VR turning so the change in net force was zero. This result might be the most critical and distinctive feature between VR and OG turning. To keep a straight path and to avoid straying from the linear treadmill, subjects seemed to exert counter forces as not to move the body's center of mass in the M-L direction on the treadmill.

Previous research reported that the increase in TA during turning indicates a greater role of the ankle dorsiflexors when changing direction [24]. Right and left TA showed increased muscle activity in OG turns compared to OG straight walking, but no significant differences were found between VR turning and VR straight walking. This finding is consistent with the minimal changes in foot position in the VR condition since the turn was not fully executed.

As well as the steady-state walking ability, which could be measured by the 10-meter walking test, ability to make gait transitions is important in rehabilitation of persons with motor disorders. Some tests have been used to assess gait ability including both of steady-state and transitions like start, stop, stair climbing, and turning [25, 26], most of which yield an overall score, but this assessment can evaluate the sequence, direction and magnitude of biomechanical changes that may be disrupted in pathology and this provide a more detailed evaluation.

In addition, to determine the mechanism of motor impairments in patients with neurological disorders such as Parkinson's disease, a safe assessment method that can reproduce episodic events such as freezing of gait (FOG) repeatedly is valuable. Our study implies that the VR turning system can be an alternate way to provide patients with those challenging environments that can arouse kinesthetic change and neurological activation. For example, some researchers utilized the VR corridor with corners when comparing cortical activation level and functional connectivity between Parkinson's disease with and without the FOG when turning [27] and they found the VR-induced changes in cortical activation. Based on functional magnetic resonance imaging (fMRI), they found that patients with Parkinson's disease and FOG showed highly activated cortical area, which is recruited to stop movement when there are conflicts in information [27] compared to patients with Parkinson's disease without FOG. Due to systematic limitations, they were only able to provide subjects with the VR corridor in the MRI scanner by depressing foot pedals. Our study provides a more realistic experience because the patients are able to walk and turn at their own pace while

experiencing the VR corridor [18], which allows for a safe, research-oriented environment that can arouse kinesthetic as well as cortical changes.

The proposed VR treadmill system may also be utilized as a training tool for gait transitions. Specially designed omnidirectional treadmill systems [14, 15] have been developed to provide comprehensive gait training but, to the best of our knowledge, those advanced systems have shown lower accessibility for patients due to the higher cost, larger size, or skill requirements. Although this study used a high-cost motion capture system, instrumented treadmill, and wireless EMG system, the VR-based turning interface can be implemented in a more affordable way by using infrared depth cameras, commercial treadmill, and IMU sensors [28] for greater accessibility as in the home or local clinics. Moreover, other gait transitions such as avoiding obstacles by controlling walking speeds could be also implemented on the VR-based system to train patients with gait disorders in various situations encountered in everyday life [8].

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Highlights

- A virtual reality-based walking interface with a linear treadmill was suggested.
- The VR-based walking system was verified to initiate turning mechanism.
- The suggested system evoked turning mechanism including kinetic and kinematic changes.

FIGURE 1.
Experimental setup (left) for (A) the overground and (B) treadmill turning with VR system
(down) with maps (C and D) that used for each test.

FIGURE 2.

Block diagram of the control of the suggested turning training system with the treadmill and the virtual reality system.

FIGURE 3.

Temporal-spatial mean ($\pm$ s.e.m.) group values (meters) for straight walking (average of three gait cycles preceding turn), the gait cycle of turning initiation (Turn), the cycle preceding the turning initiation (Turn-1), and the cycle following the turning initiation (Turn +1). (A) Step length significantly longer in cycle preceding the turning initiation and (B) step width significantly longer in cycle after the turning initiation.

FIGURE 4.
Comparison of (A) medial-lateral (M-L) GRF and (B) normalized integral of M-L GRF (mean $\pm$ s.d.) between the VR straight walking (dashed lines) and the VR turning (solid lines). (* $p < .05$)

FIGURE 5.
Muscle activation levels (Root mean square values of surface electromyography with s.d.) from Tibialis Anterior (TA), Medial Gastrocnemius (MG), Rectus Femoris (RF), and Medial Hamstrings (MH) during the left OG turning (blue solid), OG straight (red solid), VR turning (blue hatched), and VR straight walking (red hatched) conditions. (* significant difference compared to the straight walking, $p < .05$)

Table 1
Mean ($\pm$ s.d.) of peak kinematics (deg) for each condition.

All values were averaged over trials (10 for VR straight, 20 for VR turn, and 5 for OG straight and turn) and nine subjects.

Angles	VR Straight	VR Turn	OG Straight	OG Turn
Head-Lab	3.47 (1.41)	25.62 (11.41) **	1.91 (0.64)	97.73 (5.56) **†
Head-Pelvis	4.49 (1.84)	23.27 (11.82) **	5.93 (2.02)	23.73 (6.43) **
Pelvis-Lab	5.13 (1.95)	9.49 (3.05) **	5.52 (2.96)	95.73 (3.23) **†
R Hip ADD	5.34 (2.38)	5.95 (2.58)	7.27 (2.71)	7.40 (1.98)
R Hip ABD	-6.76 (3.09)	-8.34 (2.83) **	-7.59 (3.30)	-9.63 (3.81) *
L Hip ADD	5.18 (2.21)	6.06 (2.60) **	7.70 (3.31)	9.99 (2.20) **†
L Hip ABD	-6.43 (2.76)	-7.57 (3.09) **	-7.29 (2.41)	-7.22 (2.96)
R Foot-Lab	-7.51 (6.08)	-4.53 (6.79) **	-6.88 (5.09)	84.10 (7.10) **†
L Foot-Lab	-17.73 (5.71)	-20.58 (5.35) **	-16.22 (7.36)	-124.40 (14.52) **†

*
 $p < .05$

**
 $p < .005$ compared between VR turn and VR straight

OG turn and OG straight walking.

†
 $p < .001$, compared between VR turn and OG turn.)